Characterization of low-density HEDP laser target foam components using monochromatic soft x-ray sources

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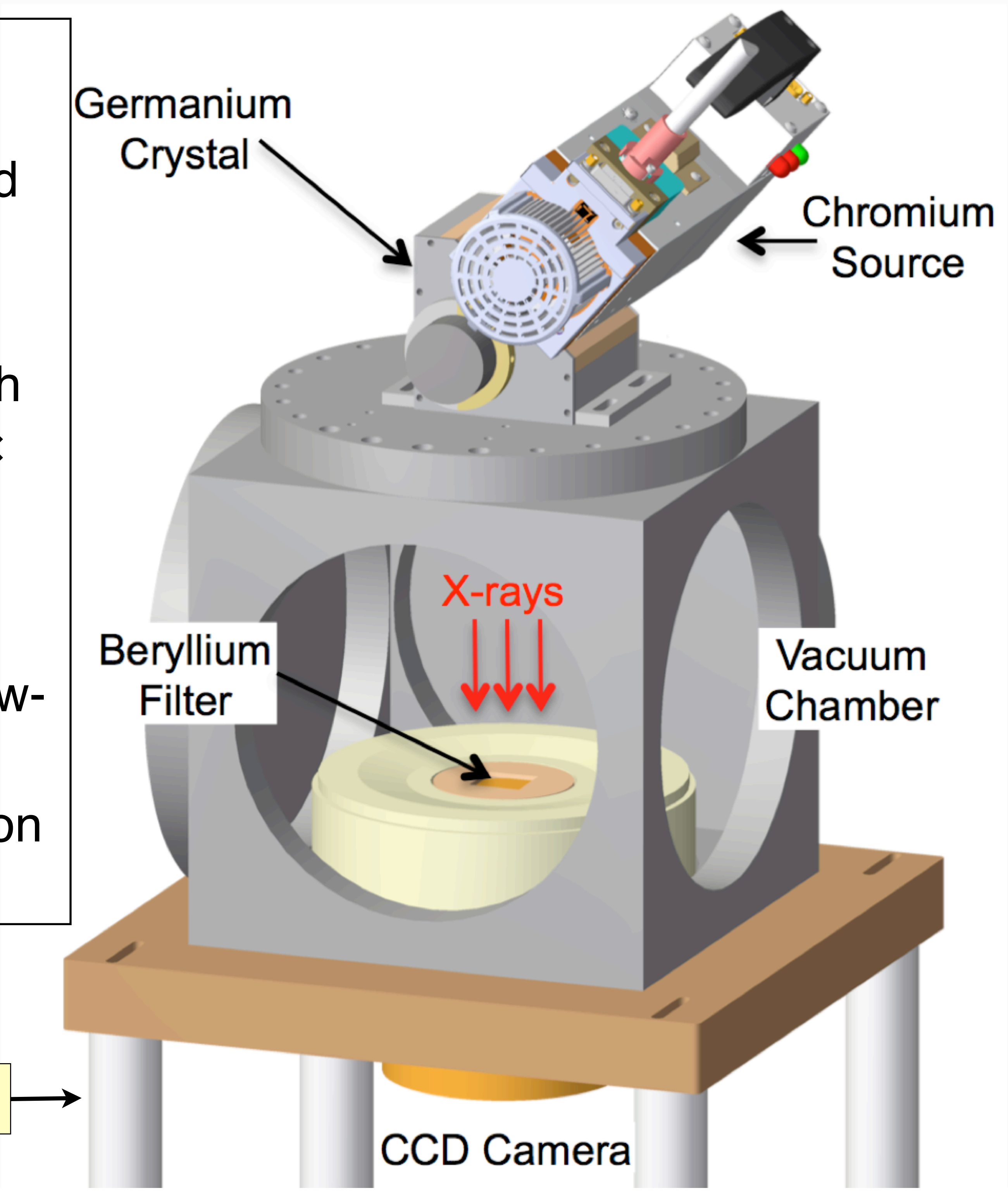
We require accurate characterization of low-density foam components for successful radiation flow experiments on NIF and Omega

- Small deviations in foam density dramatically impact radiation propagation and complicate assessment of flow models
- Foam density is currently characterized in bulk and assumed to stay unchanged during machining
- Individual components are too light to weigh, thus normally do not make density measurements of single parts
- For this reason we constructed a monochromatic x-ray imager to measure the x-ray transmission of single component foams, used to derive a line-averaged density
- For best results, this measurement should be performed in conjunction with ICP-MS (inductively coupled plasma mass spectrometry) analysis, to constrain impurity levels
- Depending on the size and density of the part in question, the density measurement uncertainty can reach the limiting factor of the cold opacity uncertainty, ~ 1%

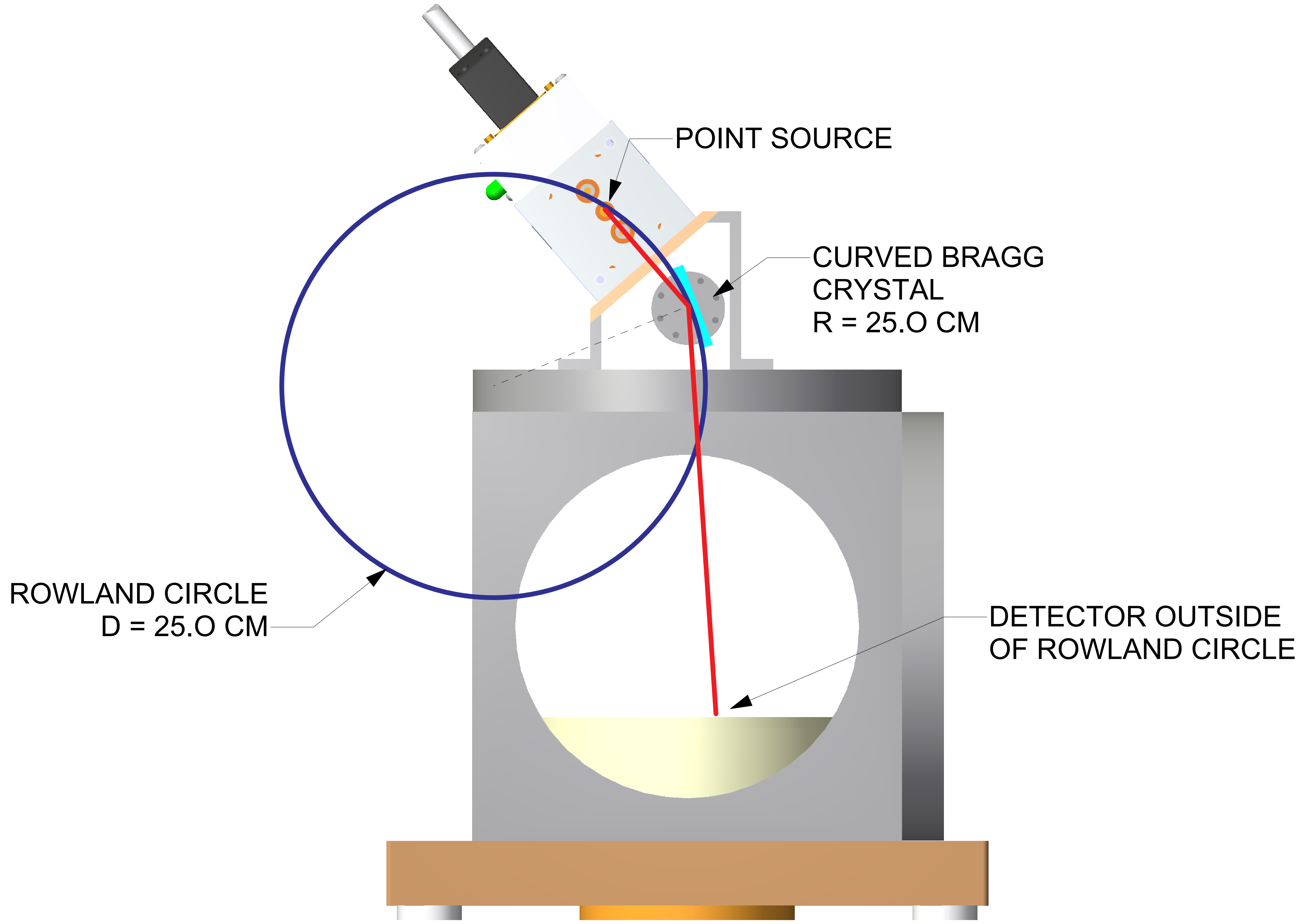
We measure the transmission of soft x-rays through low-density foam components

- The x-ray imager consists of a soft x-ray generating device at either 2.3 or 5.4 keV, each with a dedicated sample chamber and CCD camera
- Recently re-configured to use contact radiography: X-rays are transmitted through the sample and imaged onto a CCD at ~1× magnification, recording line-averaged transmission as a function of position
- The soft x-rays are in the right regime to measure very small density variations in low-density C_8H_8 and SiO_2 foam targets
- We can measure line-averaged transmission to within ~ 1% relative uncertainty



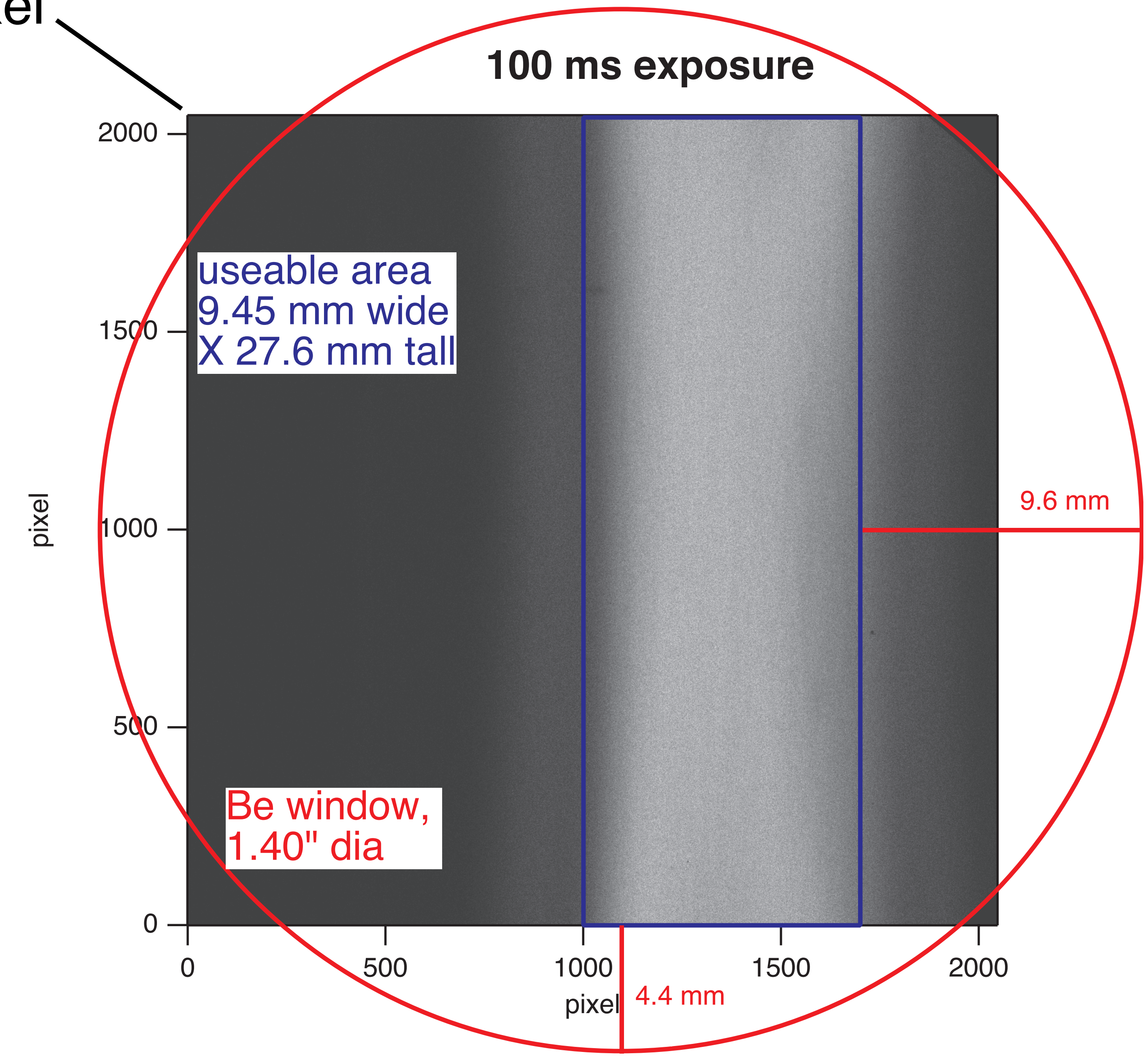
Chromium Kα (5.4 keV) setup

We illuminate a larger area of the detector by locating it outside the Rowland circle



The x-ray beam covers enough area on the detector to allow characterization of most HEDP target foams

2048 x 2048 pixel CCD image



With knowledge of cold opacity, high resolution monochromatic transmission measurements constrain line-averaged density

Change in intensity as light passes through an absorptive medium

$$dI(v,z) = -\underset{\uparrow\ \text{opacity}}{k(v)}\,\underset{\uparrow\ \text{density}}{\rho(z)}\,\underset{\uparrow\ \text{intensity}}{I(v,z)}\,\underset{\uparrow\ \text{distance}}{dz}$$

Solving for intensity and integrating over path length

$$\int \frac{dI(v,z)}{I(v,z)} = -\int k(v)\rho(z)\,dz$$

$$\ln I(v,z) - \ln I_0(v,z)$$

$$= -\int k(v)\rho(z)\,dz = -k(v)\bar{\rho}\int dz = -k(v)\underset{\text{line-averaged density}}{\bar{\rho}}z$$

thus $\boxed{I(v,z) = I_0(v,z)e^{-k(v)\bar{\rho}z} \text{ (general formula)}}$

We use a Dirac delta function for the monochromatic source and integrate over v

$$\int I(v,z)\delta(v-v_0)\,dv = \int I_0(v,z)e^{-k(v)\bar{\rho}z}\delta(v-v_0)\,dv$$

or

$$I(v_0,z) = I_0(v_0,z)e^{-k(v_0)\bar{\rho}z}$$

mono-energetic cold opacity

And then solve for the line-averaged density

$$\boxed{-\ln\frac{I(v_0,z)}{I_0(v_0,z)} = -\ln T(v_0,z) = k(v_0)\bar{\rho}z \quad \therefore \quad \bar{\rho} = -\frac{\ln T(v_0,z)}{k(v_0)z}}$$

Taking partial derivatives obtain error terms for T, k, z

Line-averaged density $$\bar{\rho} = -\frac{\ln T(v_0, z)}{k(v_0)z}$$

Take partial derivative to obtain each error term

$$\partial\bar{\rho} = \left|\frac{\partial\bar{\rho}}{\partial T}\right|\partial T + \left|\frac{\partial\bar{\rho}}{\partial k}\right|\partial k + \left|\frac{\partial\bar{\rho}}{\partial z}\right|\partial z$$

$$= \left|\frac{1}{T(v_0, z)k(v_0)z}\right|\partial T + \left|\frac{\ln T(v_0, z)}{k(v_0)^2 z}\right|\partial k + \left|\frac{\ln T(v_0, z)}{k(v_0)z^2}\right|\partial z$$

Transmission error term | Opacity error term | Axial Distance error term

For opacity and axial distance we can assume the following uncertainties:

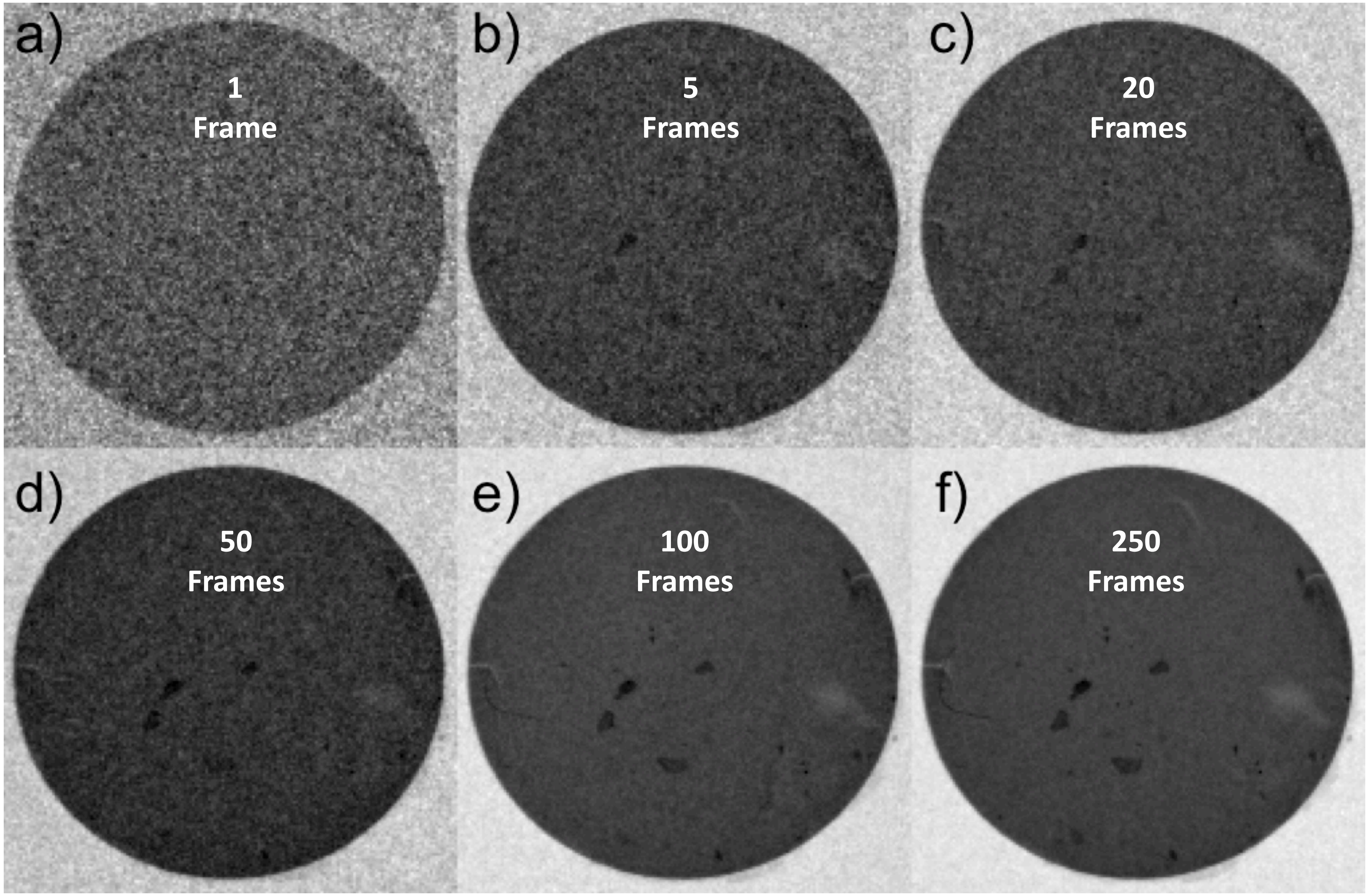
Cold opacity $\rightarrow \dfrac{\partial k}{k(v_0)} = 1\%$ and Distance $\rightarrow \partial z = 1\ \mu$m

The experimental error in the x-ray transmission measurement is dominated by photon statistics

Sample Specifications

SiO_2
$\rho \sim 125$ mg/cc
$h = 200\ \mu m$
$d = 2000\ \mu m$

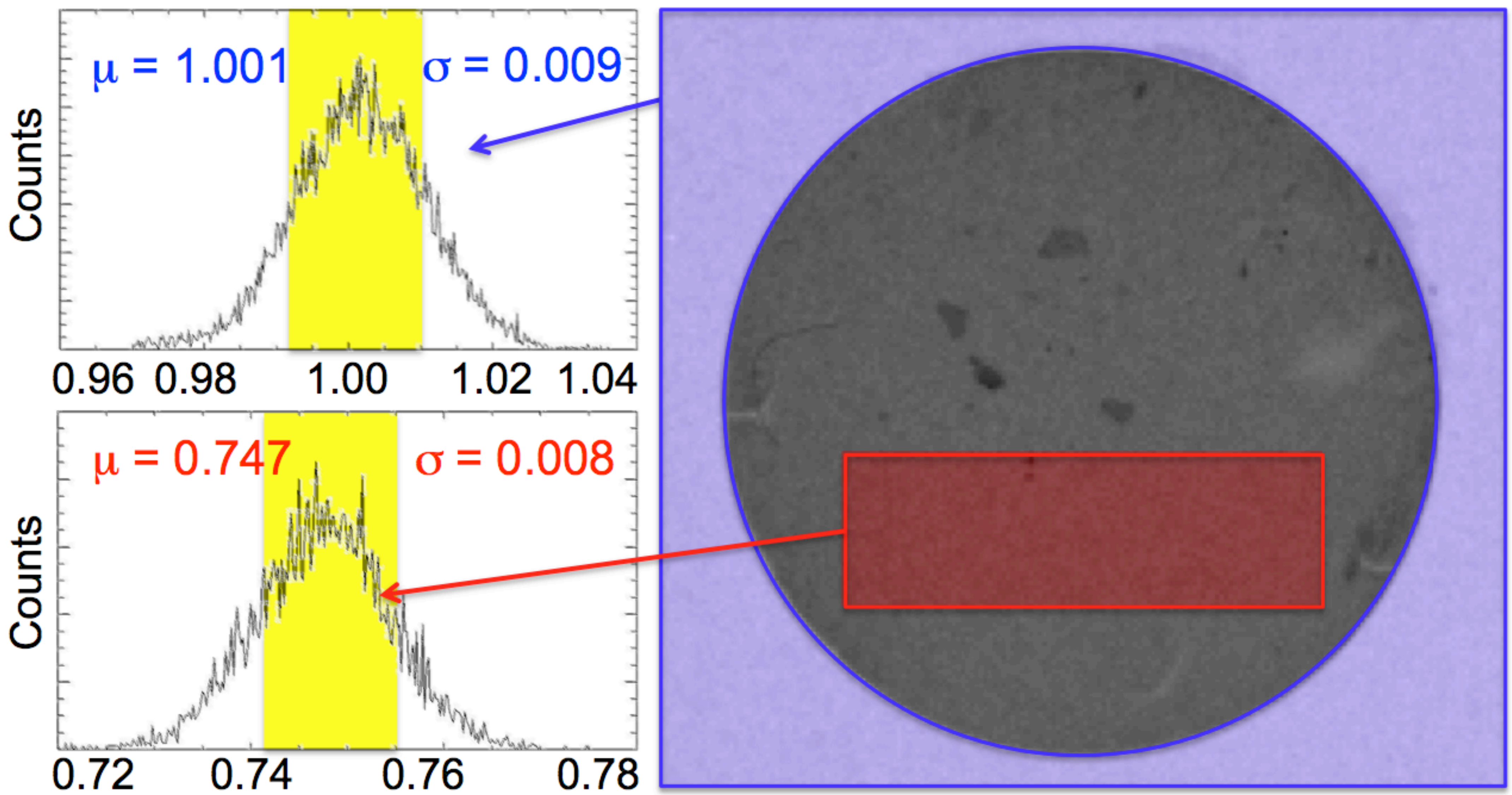
$m \sim 78\ \mu g$



All subsequent results are extracted from 250 accumulated images

The pixel-to-pixel uncertainty is ~ 1%, greater reductions are achieved by averaging over larger regions of interest

Pixel-to-pixel variation for 250 frame ensemble



A 75-μm by 75-μm region of interest yields a σ_T ~ 0.2%

Densities inferred with our x-ray assembly are statistically equivalent to measurements made at Brookhaven's NSLS

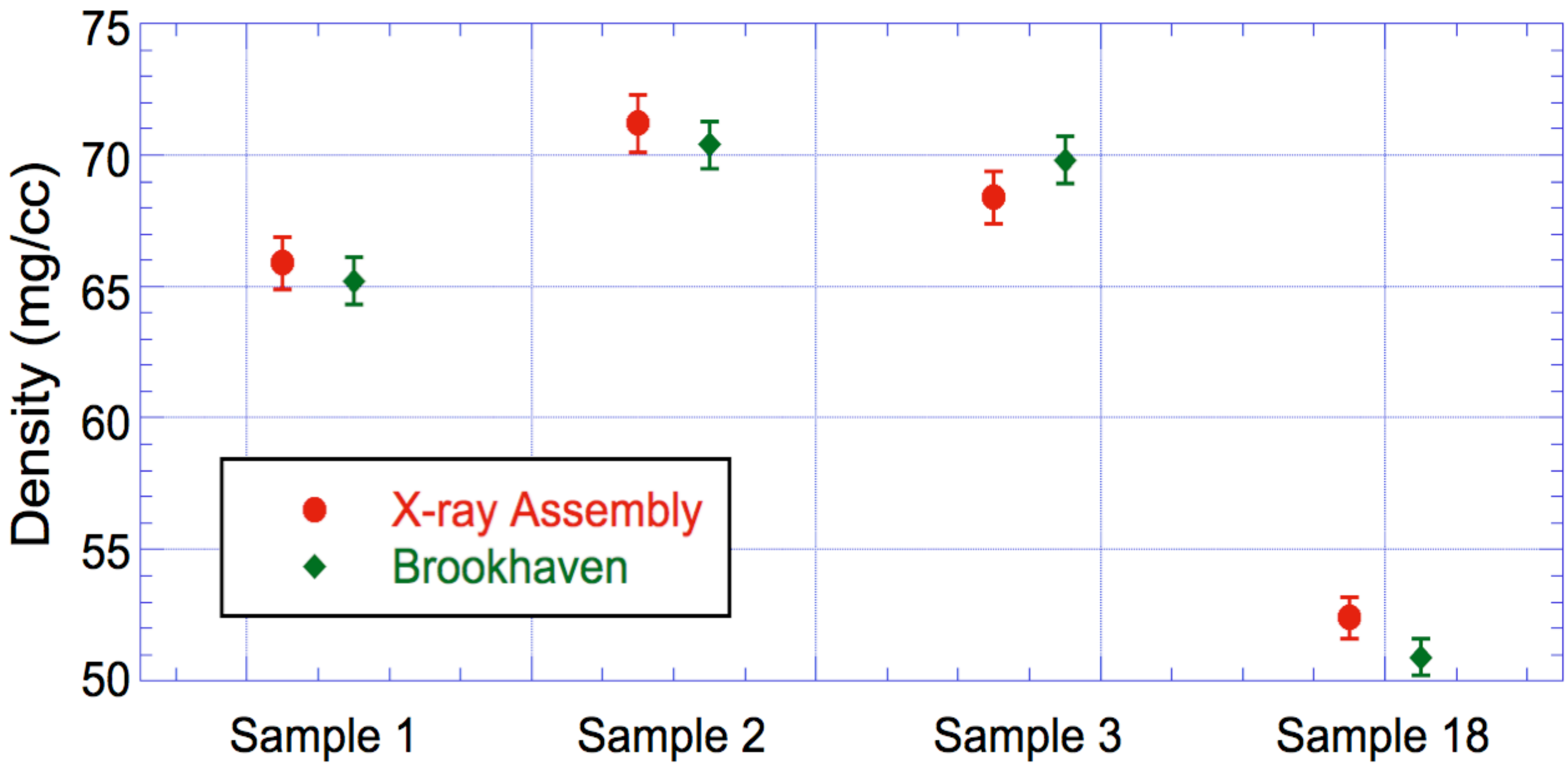
	X-ray Assembly	NSLS
Transmission @ 5.415 keV	59.4 ± 0.8 %	59.0 ± 0.5 %

~ 15 μm Silicon Standard

Sample Specifications

SiO_2
$\rho \sim 70$ mg/cc
$h = 200\ \mu m$
$d = 400\ \mu m$

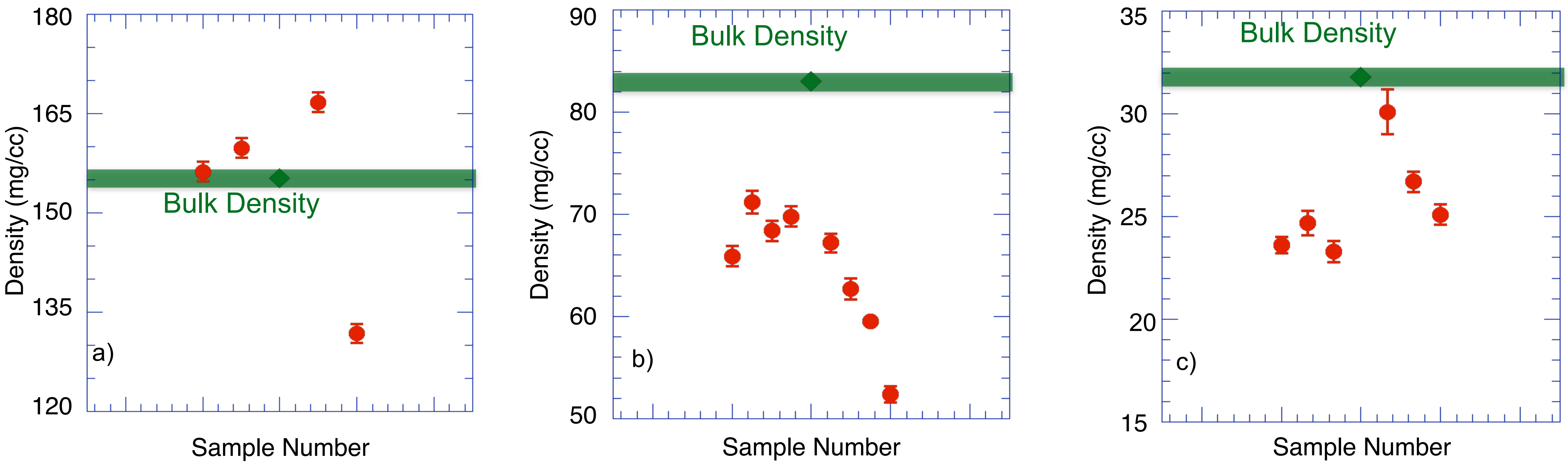
$m \sim 2\ \mu g$



A blind study provided the best option to challenge our foam manufacture and characterization techniques

- Multiple SiO_2 samples at three desired densities were manufactured
- Each sample was 200 microns thick with a 400 micron diameter
- Densities would range between 10-160 mg/cc and were cast in place
- Since overall part mass was too small for gravimetric measurements, bulk witness samples were manufactured and characterized
- Samples were also characterized on the x-ray DCS
- A subset of samples would also be characterized at Brookhaven National Laboratory's NSLS

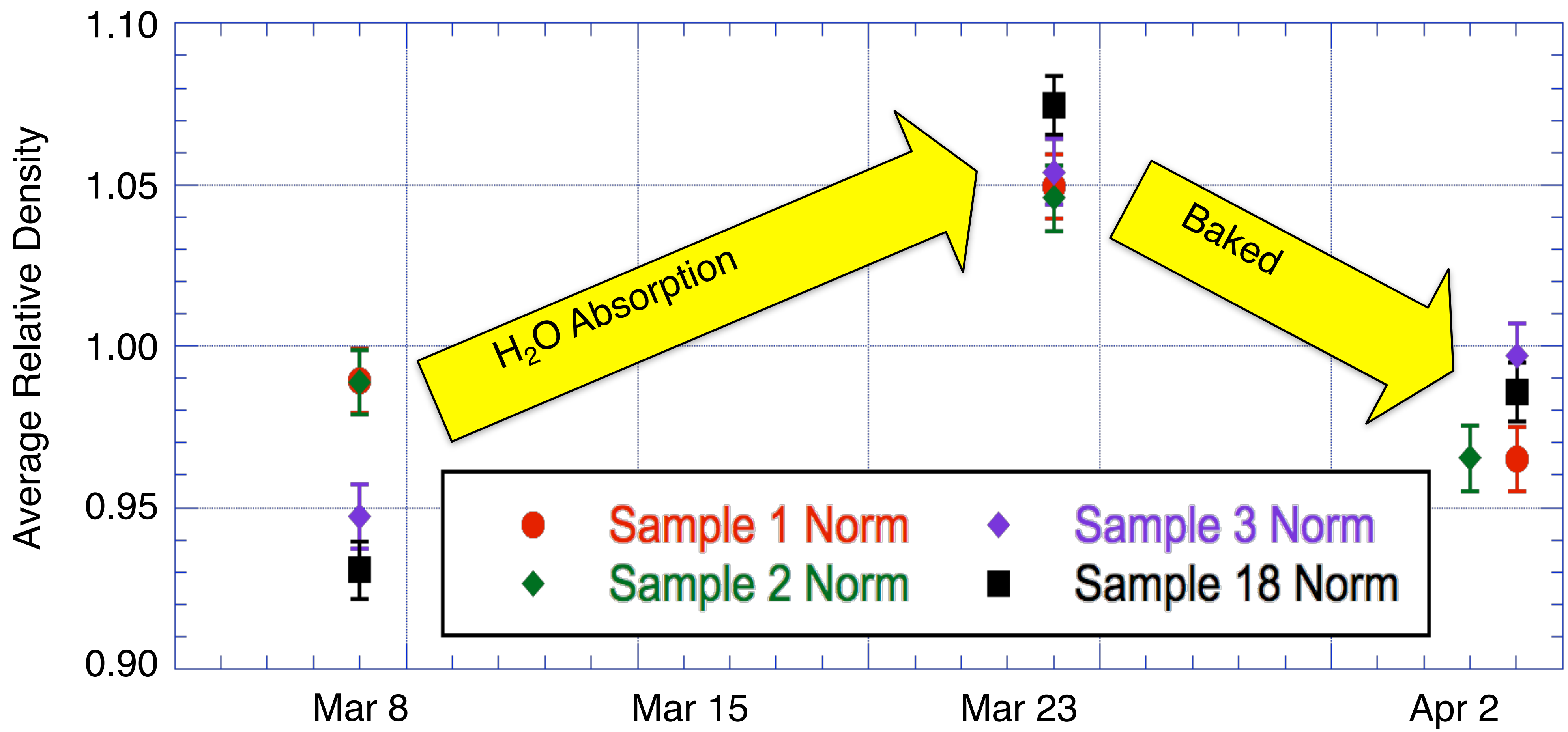
Blind study results show the bulk density often differs significantly from individual samples



- Bulk density measurements for witness samples disagree with that derived from x-ray transmission for small cast in place SiO_2 foams
- Significant variability existed between samples of supposedly identical density
- The x-ray DCS clearly resolves this variability

Increased water content can lead to higher inferred densities if not properly accounted for

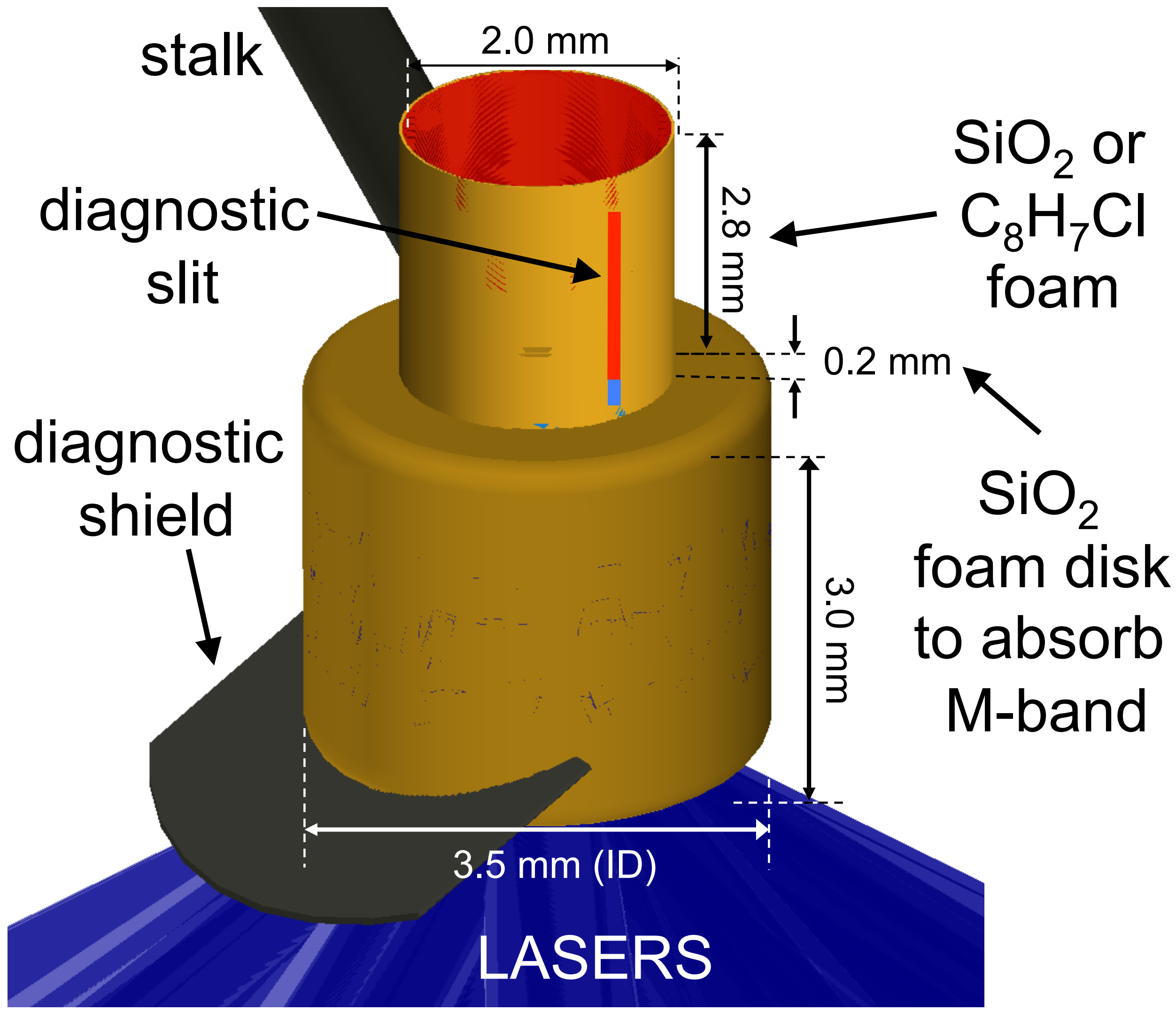
X-ray assembly data showing the hygroscopic nature of SiO_2 foams



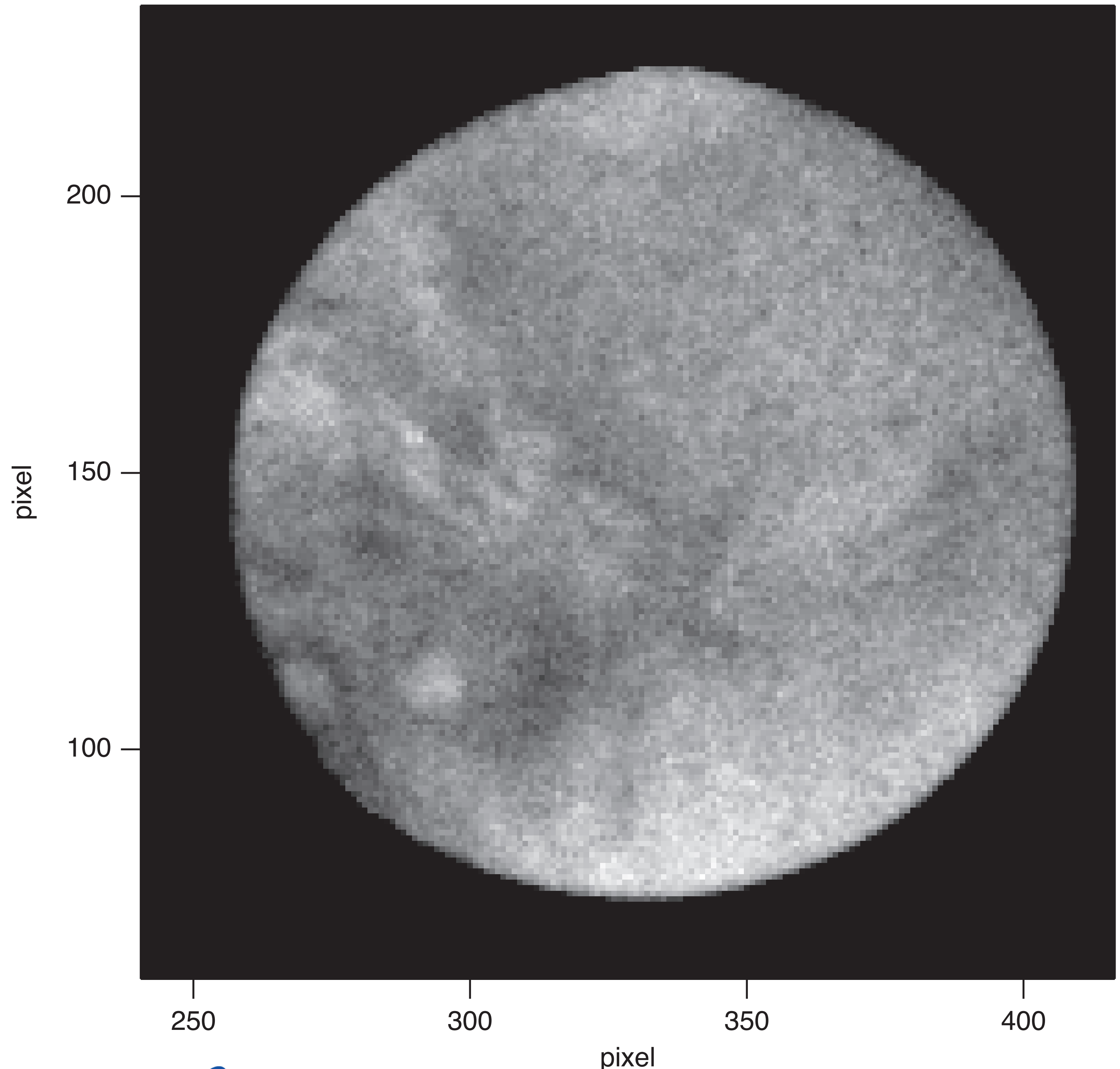
After baking, the densities approach their original values.

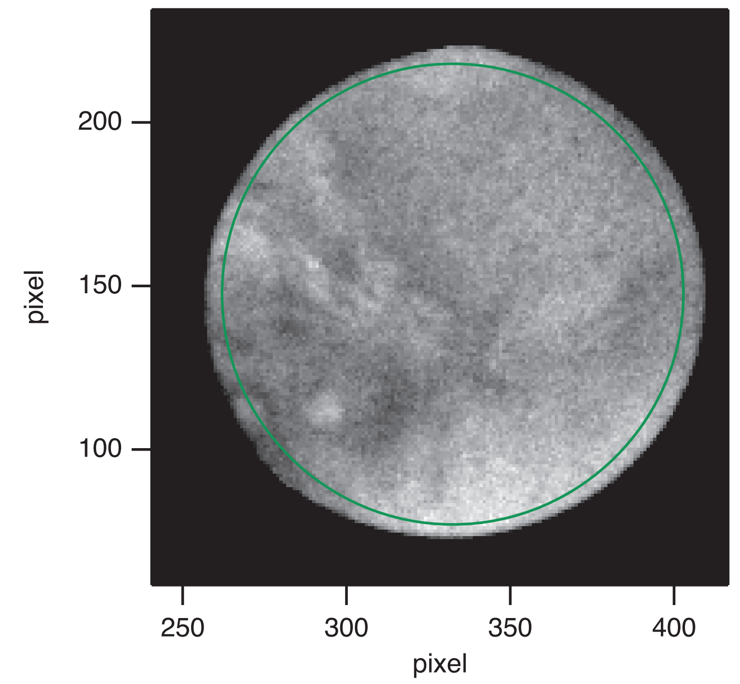
Foam density characterization station is already impacting selection of NIF HEDP targets

- Our x-ray assembly is impacting the first set of non-ignition related experiments being performed at NIF in support of development and validation of models used in our codes
- HEDP targets include 125 mg/cc silica aerogel or chlorinated plastic foams that require detailed characterization



Some targets, such as this HiPE (C_8H_7Cl) one - were eliminated from our shot sequence after characterization





Averaging over ROI:
ρ_{avg} = 124.0 ± 1.3 mg/cm^3
($\rho_{witness}$ = 126 mg/cm^3)

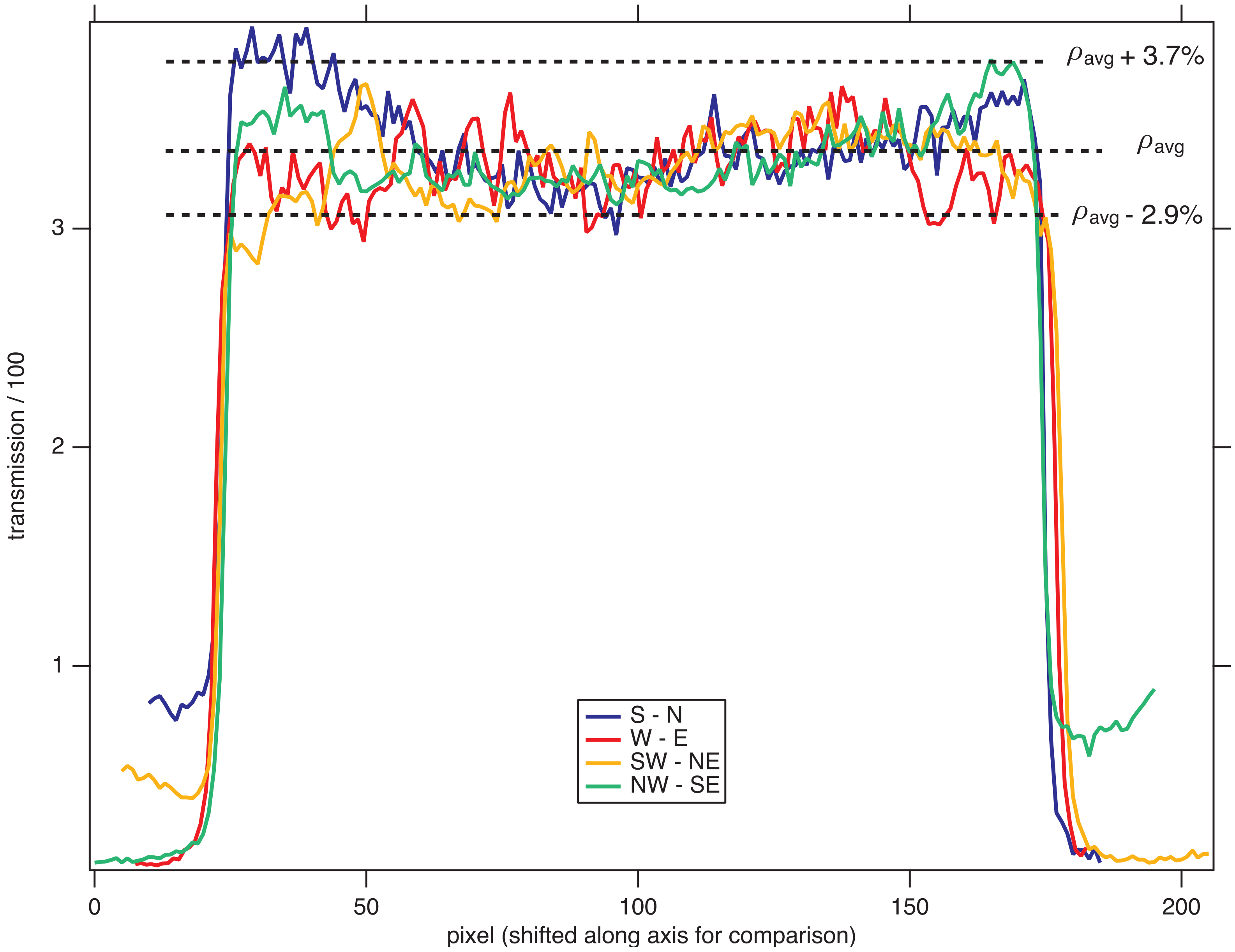
Assumptions:

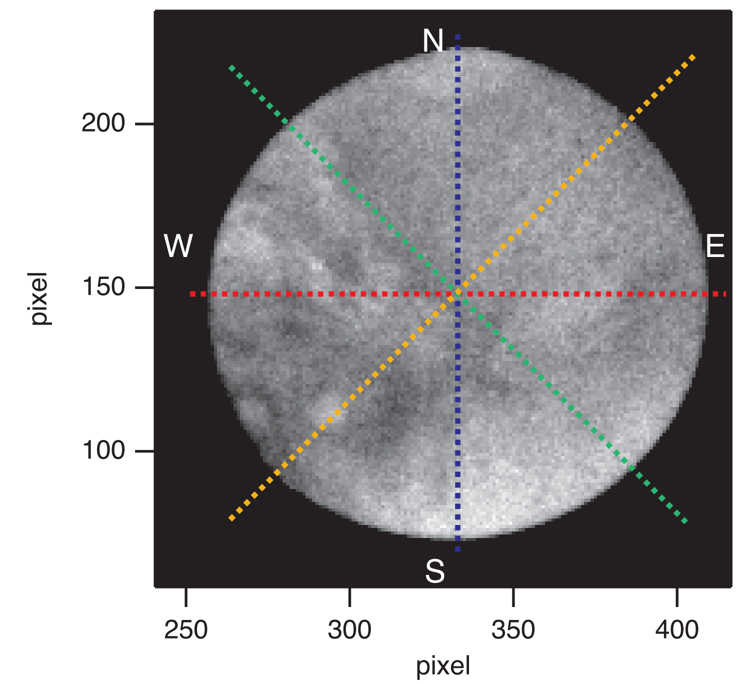
HiPE cold opacity @5415 eV = 90.3 cm^2/g ± 1%

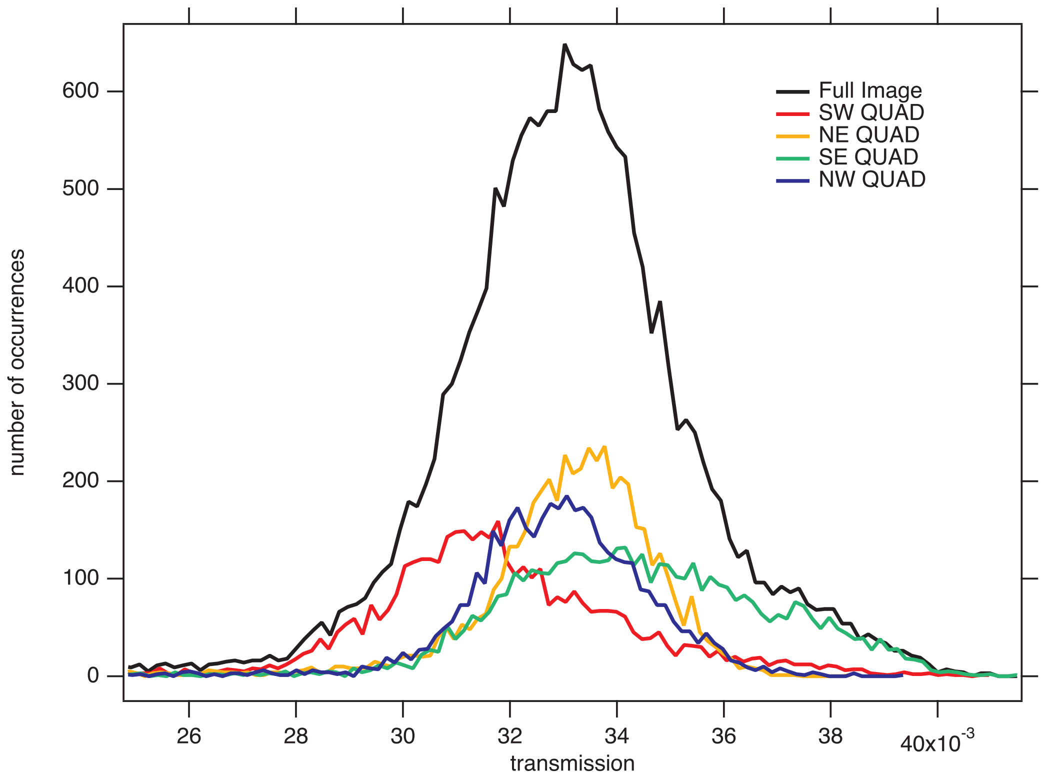
thickness error is ± 1 μm

The x-ray assembly also provides a good test of density uniformity

ρ_{avg} = 124.0 ± 1.3 mg/cm³







Summary

- We have constructed a monochromatic x-ray imager to quantify the density of low-mass single component foams
- Density inferences from the x-ray assembly are identical to those obtained at NSLS
- Small cast-in-place SiO_2 foams often exhibit high variability in their density, and are poorly represented by bulk measurements on witness samples
- For the masses and sizes tested, the x-ray assembly resolved line-average transmission down to ~1%
- When left exposed to air, the SiO_2 samples absorbed water, leading to an increase in inferred densities
  - easily resolved by the x-ray DCS
  - more characterization of this effect is essential to assure foam components at the time of experiments are understood
- Current efforts implementing 2.3 and 8.0 keV sources are underway